MASONRY MORTAR

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ATLANTA UNIVERSITY, ATLANTA, GEORGIA

Lime-Cement Mortar

ARCHITECTS	BUILDER
JAMES GAMBLE ROGERS, INC.	BARGE-THOMPSON COMPANY

Rindge Technical High School, Cambridge, Mass.

Durable, water-tight masonry laid up with mortar composed of two volumes lime putty, one volume cement and seven volumes of sand.

ARCHITECT: RALPH HARRINGTON DOANE — GENERAL CONTRACTORS: GEORGE A. FULLER CO.

MASONRY MORTAR

Rely on LIME
-tested by time

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Properties of Mortars and order in which they are discussed

CHRYSLER BUILDING
NEW YORK

ARCHITECTS:
JAMES VAN ALEN

BUILDER: FRED T. LEY

Leak-proof masonry laid up with 1:3 lime mortar to which not more than 4 bags of cement were added to each cubic yard of mortar.

MASONRY MORTAR

DRY WALLS WITH LIME MORTAR

A WATER-TIGHT masonry wall has a negligible number of unfilled joints or open spaces where brick and mortar apparently meet but are not attached. The formation of such openings is influenced by the properties of the materials used and class of workmanship employed. The presence of openings between units and mortar is the primary cause of *excessive water penetration* into the wall. The excess water may or may not enter into the interior of a building as a result of this condition. If it does, the wet interior is a symptom of the condition. Repeated and prolonged efflorescence on the exterior of the wall is another symptom. The condition, however, may exist without these symptoms. This condition must be prevented if the masonry is to be durable. No material, however weather resistant it may be, can endure for many years, under conditions of excessive saturation. The most effective method of preventing the condition, wet walls, is to lay up the masonry in a mortar having properties which will permit the mason to completely fill all joints. The mortar should also possess properties which permit formation of maximum extent of bond plus ability to maintain such bond.

The fact that openings exist is proved by the many instances of leaky walls wherein both units and mortars are comparatively impervious. Mortars of very low porosity are often associated with bad leaks. Water follows the path of least resistance, through the openings between the masonry materials, not through these materials.

Water that enters pores and voids of bricks, stones, mortars, etc., readily evaporates from the exterior surface. This is a normal condition offering no cause for concern.

The alarming increase in number of leaking buildings during recent years led to an extensive program of research at the National Bureau of Standards, the Massachusetts Institute of Technology, the Mellon Institute of Industrial Research and other recognized institutions. The problem has also been intensively studied by leading authorities in Europe, particularly in Great Britain and Sweden. The data resulting from these various studies have been analyzed and the following discussion prepared in an effort to place authoritative information at the disposal of American architects, engineers, building officials, builders and others.

Assuming proper design, adequate inspection during construction and good workmanship, the most important factor in obtaining a water-tight wall is the selection and use of a mortar properly adapted to the units, taking into consideration the nature and severity of exposure.

Adaptability of Mortars

To prevent excessive water penetration into a wall, one must use an *adaptable mortar*. This is a mortar that can be expected to *adhere satisfactorily to all types of building units*.

Lime promotes mortar adaptability and a mortar rich in lime is suitable for all types of units. An adaptable mortar is first of all *workable*. It has *bonding power*. It is characterized by low volume changes subsequent to hardening. It has good extensibility, produces good masonry strength and has a rate of hardening compatible with modern methods of construction. These properties will be discussed in the light of the results of research in the masonry field.

PROPERTIES OF A MORTAR THAT MAKE IT ADAPTABLE AND SUITABLE

1. *WORKABILITY*

Until recent years the term, workability, has been poorly understood in its application to masonry mortars. Warren E. Emley in Bureau of Standards Technologic Paper No. 169 states:

"The *ability to retain water*, while the *most important*, is not the only factor governing plasticity." Due to the fact that water retaining capacity is the most important factor governing plasticity and further to the fact that this property has been found to be always associated with plasticity, it may be said that a measure of the water retaining capacity of a mortar provides a good index to its plasticity or workability.

A factor of lesser importance is the bulk density or weight per unit volume of the freshly mixed mortar. Still another factor is its "trowelability" which may be estimated by the difficulty or ease of forcing it into the interstices of a brick surface of very rough texture. The three known factors that control workability are then:

1. Water retaining capacity
2. Bulk density
   and
3. Good troweling properties

(A) *Water Retaining Capacity*

The method of measuring the water retaining capacity of different mortars and the enhancement of this property by the substitution of more and more lime for portland cement in lime-cement mortar mixtures are dis-

cussed in a paper, "Rate of Stiffening of Mortars on a Porous Base," appearing in the September 10, 1932, issue of Rock Products. These data were obtained during the course of an extensive cooperative investigation of masonry mortars at the National Bureau of Standards. The index to water retaining capacity was taken as the flow of a mortar on a 10-in. flow table after it had been subjected to suction on a standard porous base for a definite time interval, 1 minute, 2 minutes, etc. The suction was equivalent to that of a very porous dry-press brick laid dry in the wall. Water is the sole lubricating medium in mortar and the more retentive it is of water, the more workable is the mortar under practical working conditions. If the mortar loses water to the brick too rapidly, it stiffens so quickly that intimate contact is not made and as a consequence the mortar adheres to the brick only in spots. In other words the extent of bond is poor. If the mortar has high water retaining capacity the extent of bond is good.

Water is transmitted readily through the unbonded areas, *i.e.,* where brick and mortar *apparently* meet but are not attached. This was proved by actual tests at the National Bureau of Standards. Typical data are given in Table 1.

TABLE 1

Water Retaining Capacity of Mortars as Related to the Water-tightness of Test Walls

Mortar Composition Lime: Portland Cement: Sand Proportions by Volume	Water Retaining Capacity (Flow per cent, after suction for 1 minute on a standard porous base)	Maximum rates of leakage of 8-inch test walls made with Dry-Press bricks set dry. (Cubic centimeters of water transmitted through walls per min.)
0.15:1:3	54	402
1:1:6	75	386
2:1:9	93	98
3:1:12	91	128

Figure 1 illustrates what is meant by "mortar pancakes." These frequently occur with mortars of low water retaining capacity. As is apparent, the adhesion of the mortar to the bricks was initially very poor. The bricks held together for at least 4 weeks but later came apart due to volume changes in the mortar occurring subsequent to its hardening.

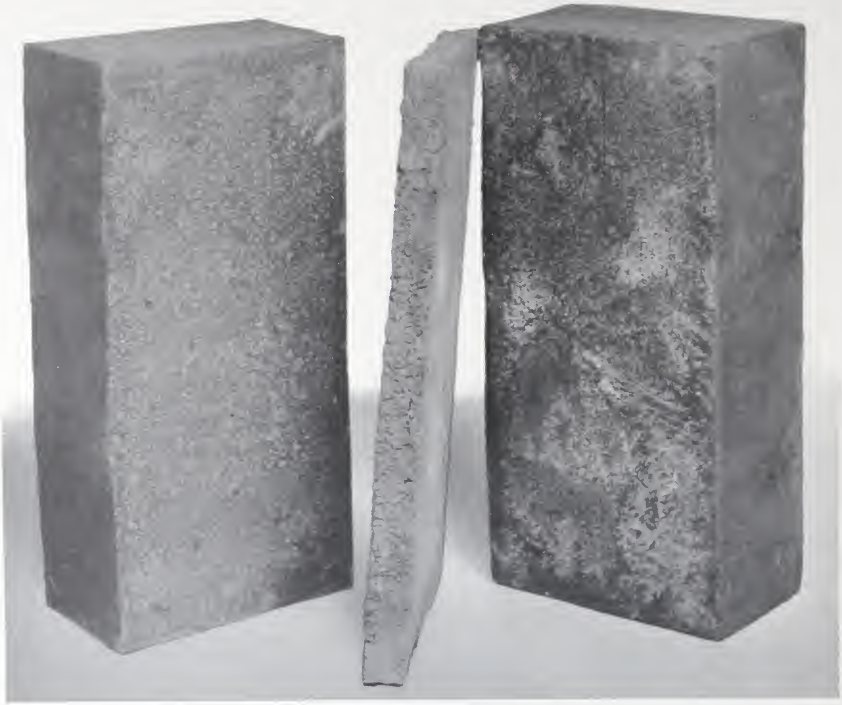

FIGURE 1

A 1:3 portland cement and sand mortar and porous dry-press bricks set dry. The mortar pancake was very dense and had high strength. A wall wherein this condition exists would have neither strength nor water-tightness.

Bricks identical to those in Figure 1 were wetted by complete immersion in water for 15 minutes and then laid with this same 1:3 portland cement mortar in making brick beams for flexure tests. The mortar having low water retaining capacity when remaining on a base that will not absorb an appreciable amount of water will undergo segregation and form "puddles." The reader can see where puddies were in Figure 2 which is typical. The bricks were found to be separated at the end of 3 months when the beam was picked up to be tested. Volume changes in the hardened mortar had again done their work. In Figure 2, practically all of the mortar joint is seen attached to the lower brick. There is a very thin film (cement particles mostly) over the flat surface of the upper brick. Unbonded areas are also seen. The bond was weaker than the mortar, a condition characteristic of mortar having poor bonding power.

It is difficult to get a satisfactory bond with a mortar deficient in water

FIGURE 2

Poor extent of bond. Porous bricks set wet (15 minutes total immersion in water) with a 1:3 portland cement and sand mortar. Note depressions in surface of mortar joint (right) due to puddles being formed by segregation in the mortar before top brick was placed. The bond failed completely weeks after mortar hardened. Failure was caused by volume changes which occurred subsequent to hardening of mortar.

retaining capacity, no matter what the absorption of the brick may be. The results obtained with such a mortar and impervious bricks are comparable to those illustrated in Figure 2 and obtained with porous bricks that have been thoroughly wetted before laying them. Figure 1 shows what a porous brick laid dry with a mortar of *low* water retaining capacity will do. With a brick of medium rate of absorption there is still trouble with this kind of mortar. The mortar will tend both to segregate and stiffen too rapidly, the more of one than of the other, dependent on the absorption rate of the unit and the speed of bricklaying, this type of mortar being very "sensitive" to slight variations in the absorption rate among bricks of a kind.

The data in the last column of Table 1 were obtained by tests that were extremely severe, far more so than the conditions to which a wall may be

exposed in the most severe rain storm. The extent of bond obtained with the 2 lime: 1 portland cement: 9 sand and the 3 lime: 1 portland cement: 12 sand mortars in the walls subjected to these severe tests, was *complete* and for all practical considerations the test walls would have been water-tight had they been integral parts of an 8-inch wall. Practically all of the water that came through the test walls with these mortars, followed through along the porous header bricks. Furring would check this in a wall.

(B) *Bulk Density*

The bulk density of a mortar is a factor of such minor importance that its discussion is not warranted. Since three-quarters of the total volume of dry ingredients is sand, there are very strict limitations imposed on any effort to make freshly mixed mortar light in weight.

(C) *Troweling Properties*

A mortar has good or poor troweling properties. The data of the last column of Table 2 were obtained with very rough textured face bricks set wet. It was observed on breaking the test walls after testing them for permeability that the non-plastic mortars did not fill the interstices of the rough faces and header ends of these bricks. Rather, they tended to bridge across these shallow indentations. The course of the water in its movement into and through the test wallettes could be traced by the stain left by the dye that was in the water and it was noted that water moved under the "mortar bridges" and over the bottom of the depressions when the bricks were laid in non-plastic mortars. The more workable mortars gave very little evidence of this condition.

TABLE 2

Average Rates of Water Transmission Obtained with Different Mortars and a Rough Surfaced Brick Set Wet

Mortar Lime: Cement: Sand By Volume	Troweling Properties	Average maximum rates of water transmission through test wallettes. Averages for 3 specimens. Cubic centimeters per minute.
0.15:1:3	Very Poor	226
1:1:6	Good	43
2:1:9	Excellent	40
3:1:12	Superior	26
1:0:3	Good	36

These data were obtained at the National Bureau of Standards during the cooperative study of mortars for unit masonry.

2. *BONDING POWER*

This property is not so intangible as its name implies. A mortar having this property really takes hold on a solid surface. If a mortar can't take hold, can't attach itself to a building unit under certain conditions, then it has no bonding power under those conditions. We may strive to change the conditions by wetting the brick, etc. However, it is a nuisance to have to do this and moreover we never know when we have done it satisfactorily.

Strength is only one of the factors determining bonding power of a mortar. Often (see Figure 1) it is a factor of small importance. We are not concerned so much with what a mortar *can be made to do* with extreme care and careful nursing in a laboratory, as we are with what it *does do* with *reasonable care* either in a laboratory or in a wall of masonry. With extreme care a poorly adaptable mortar of low water retaining capacity and high volume changes subsequent to hardening may bond well in the sense that it adheres completely to the unit at all points of contact. In such a case the section of failure in tension is practically always entirely at the plane of contact of brick and mortar and not in the mortar itself. *In other words, under the most favorable conditions,* a poorly adaptable mortar will *always have a bond strength that is less than the tensile strength of the mortar.*

Bonding power involves general adaptability. Bonding power is that property of a mortar which gives it a tendency to adhere uniformly and completely at all points of contact where bricks and mortar meet, under widely different conditions and with various types of units, the intensity of its adhesion being such that the tensile strength of bond is either equal to or greater than that of the mortar.

With reference to two mortars, one being a 1 lime: 1 portland cement: 6 sand and the other a 1 portland cement: 3 sand mortar (proportions by volume), conclusion No. 6 of Bureau of Standards Research Paper No. 290, "Durability and Strength of Bond Between Mortar and Brick," reads as follows: "The ratio, strength of bond to tensile strength of mortar, *was greater with the 1:1:6 than with the 1:3 mortar.*" More recent data, published in Bureau of Standards Research Paper No. 683, "The Properties of Bricks and Mortars and Their Relation to Bond," show conclusively that mortars richer in lime than the 1:1:6 mix have

Chicago Historical Society, Lincoln Park, Chicago, Ill.

ARCHITECTS: GRAHAM, ANDERSON, PROBST & WHITE CONTRACTOR: LUNDOFF-BICKNELL CO.

Lime-Cement Mortar mixed in the proportion of two volumes lime, one volume cement and nine volumes of sand.

TABLE 3

TABLE 3

Bonding Power of Mortars as Indicated by the Ratio of Strength of Bond to Compressive and Transverse Strength of Mortars at 3 Months Aging Period

Mortar Composition Lime: Cement: Sand (By Volume)	Compressive strength of mortar at 3 mos.	Transverse strength of mortar at 3 mos.	Brick	Suction of brick when laid. Grams of water absorbed through flat surface in one minute	Ratio, bond strength at 3 mos. to compressive strength of mortar at 3 mos.	Ratio, bond strength at 3 mos. to transverse strength of mortar at 3 mos.
	lbs./in.^{2}	lbs./in.^{2}		grams		
0:1:3	1,435	472	No. 1 set dry	117	0.008	0.024
0:1:3	1,435	472	No. 1 set wet	3	0.049	0.149
0:1:3	1,435	472	No. 3 set dry	10½	0.050	0.153
0:1:3	1,435	472	No. 6 set dry	72	0.020	0.061
1:1:6 (Lime No. 1)	447	149	No. 1 set dry	117	0.052	0.156
1:1:6 (Lime No. 1)	447	149	No. 1 set wet	3	0.080	0.240
1:1:6 (Lime No. 1)	447	149	No. 3 set dry	10½	0.094	0.280
1:1:6 (Lime No. 1)	447	149	No. 6 set dry	72	0.077	0.230
1:1:6 (Lime No. 2)	686	166	No. 1 set dry	117	0.038	0.160
1:1:6 (Lime No. 2)	686	166	No. 1 set wet	3	0.059	0.244
1:1:6 (Lime No. 2)	686	166	No. 3 set dry	10½	0.076	0.314
1:1:6 (Lime No. 2)	686	166	No. 6 set dry	72	0.052	0.210
2:1:9 (Lime No. 2)	357	118	No. 1 set dry	117	0.072	0.217
2:1:9 (Lime No. 2)	357	118	No. 1 set wet	3	0.063	0.192
2:1:9 (Lime No. 2)	357	118	No. 3 set dry	10½	0.092	0.280
2:1:9 (Lime No. 2)	357	118	No. 6 set dry	72	0.078	0.236
3:1:12 (Lime No. 1)	168	109	No. 1 set dry	117	0.102	0.157
3:1:12 (Lime No. 1)	168	109	No. 1 set wet	3	0.077	0.120
3:1:12 (Lime No. 1)	168	109	No. 3 set dry	10½	0.175	0.270
3:1:12 (Lime No. 1)	168	109	No. 6 set dry	72	0.126	0.200
1 portland cement; 3 sand plus 15 per cent of hydrated lime by volume of cement	2,185	646	No. 1 set dry	117	0.0001	0.0003
1 portland cement; 3 sand plus 15 per cent of hydrated lime by volume of cement	2,185	646	No. 1 set wet	3	0.023	0.077
1 portland cement; 3 sand plus 15 per cent of hydrated lime by volume of cement	2,185	646	No. 3 set dry	10½	0.035	0.119
1 portland cement; 3 sand plus 15 per cent of hydrated lime by volume of cement	2,185	646	No. 6 set dry	72	0.007	0.025

Note: The same typical gray portland cement, meeting A.S.T.M. Standard Specifications, was used throughout.

better bonding power than that mortar. As lime, either putty or dry hydrate, was substituted more and more for portland cement, the bonding power was improved. The tensile strengths of mortar specimens were not actually measured in these tests. However, the tensile strength of mortar is approximately proportional to the corresponding compressive and transverse strengths which were measured.

Table 3 contains data typical of those obtained by these tests at the Bureau of Standards. The lime-cement mortar mixtures of Table 3 were made with one and the same portland cement. The bonding properties of the portland cement mortar and of the portland cement mortar with the addition of 15 per cent by volume of hydrated lime are given as data for the first and last mortars respectively of Table 3. The bricks listed in this table are representative of both extreme and intermediate types from the standpoint of rate of absorption.

The higher the values in the last 2 columns of Table 3, the greater the bonding power of the mortar. The greater the divergence among the ratios in these two columns (Table 3) obtained with the 4 different bricks with one and the same mortar mixture, the poorer the adaptability of that mortar and conversely.

In an article published in Part II, Vol. 33, 1933 issue of the Proceedings of the American Society for Testing Materials, Professor W. C. Voss of the Massachusetts Institute of Technology makes the following statement:

> "The position has been taken that a brick and mortar assemblage which will fail 50 per cent or more in the mortar is far superior to one which will not, *regardless of the actual strength in pounds per square inch*. Our reason for this is based upon the fact that it is more important to insure a 'bond layer' at the brick line, than it is to insure no break in the mortar."

Even this concise statement gives to high strength mortars of poor bonding power more than is their due. Note the expression, *regardless of the actual strength in pounds per square inch* and then note that the strength of bond in tension of the last mortar of Table 3 was 0.0001 times 2,185, or 0.2 lbs. per square inch with brick No. 1 (dry-press) set dry. Low bond strength obtained with such a strong mortar is well illustrated by Figure 1.

Data similar to those in Table 3, may be derived from the data of Duff A. Abrams as given in Table 10 of Bulletin No. 8, Structural Materials Research Laboratory, Lewis Institute, Chicago. Mr. Abrams tested the bond between concrete and steel by pull-out tests of 1-inch plain steel

bars imbedded 8 inches in an 8-inch concrete cylinder. In Table 10 of his publication he presents the compressive strength of 6 by 12-inch cylinders together with the maximum bond stress. In the group of tests given in this Table (10) hydrated lime *replaced* an equal volume of portland cement; therefore the quantity of cement decreased with increased percentage of lime. The values in Table 4 were computed from his data.

TABLE 4

Effect of Hydrated Lime on the Ratio, Maximum Bond Stress to Compressive Strength

Hydrated Lime, Per Cent of Cement Plus Hydrated Lime		Ratio: $\frac{\text{Maximum Bond Stress (lbs./in.}^2)}{\text{Compressive Strength (lbs./in.}^2)}$			
By Volume	By Weight	7 days	28 days	3 mos.	1 year
0	0	0.24	0.25	0.21	0.23
20	11.1	0.33	0.18	0.24	0.23
50	33.4	0.31	0.23	0.31	0.26

These values were obtained with a 1:5 mix by volume. Lean mixtures tend to have low bonding power and it is especially interesting to note a tendency for slight improvement in this property with so lean a mix with the substitution of lime for cement.

With reference to reinforced brick masonry, Professor John W. Whittemore makes the following statement in Vol. XXV, Bulletin No. 9, of the Virginia Polytechnic Institute:

> "Failure of the individual bricks in tension, bending or shear is much less likely to occur than is the failure of the *mortar joint* in tension, bending or shear. *The adhesive strength of mortar to brick is perhaps the governing factor*."

On page 47, Vol. III, Brick Engineering, Hugo Filippi states:

> "From the general performance of beams and slabs under test, however, there is some evidence that the *bond value of the mortar joint in shear is an important, if not the controlling factor*."

We have seen that to have bonding power, a mortar must have adaptability. To have adaptability it must have workability. Good bond necessitates good extent of bond. Good extent of bond under variable conditions and with different types of units can only be obtained with a mortar that is *adaptable*.

ARCHITECTS: DELANO AND ALDRICH

DIVINITY SCHOOL—YALE UNIVERSITY, NEW HAVE

BUILT [illegible]

Water-tight masonry—free from efflorescence. Mortar compose
volume cement and [illegible] volumes sand

E UNIVERSITY, NEW HAVEN, CONNECTICUT
BUILT 1933
florescence. *Mortar composed of two volumes lime, one* ement and *nine volumes sand.*

GENERAL CONTRACTORS: SPERRY AND TREAT CO.

3. *VOLUME CHANGES*

There has been more confusion in the treatment and consideration of this topic than perhaps any other. It must be borne in mind that mortars undergo three distinct types of volume changes. These are:

(A) Compacting on a porous base
(B) Shrinkage during early hardening
(C) Volume changes subsequent to hardening

The first two, (A) and (B) occur but once during the life history of a mortar. The third, (C) occurs over and over again. It is a cyclic process, the mortar expanding on becoming damp or wetted and shrinking when it again dries out. This cyclic process, alternate expansion and contraction, continues over a period of years. The first type of volume change, (A), cannot take place unless there is contact of the mortar with another material, *i.e.*, a porous body. The types (B) and (C) do not require contact of mortar with a solid object.

(A) *Compacting on a Porous Base*

a. This type of volume change is essentially unidirectional. The diminution in volume is caused chiefly by a shortening of one dimension of the mortar joint and in a direction perpendicular to the plane of contact of the mortar and solid object, such as brick, tile, etc. The shrinkage is in the general direction of the course that the water takes in leaving the mortar and entering the porous unit. *The higher the water retaining capacity of the mortar the less is its compacting on a porous base and conversely.*

b. Compacting on a porous base *occurs prior to any appreciable hardening or cementing action* that the mortar undergoes.

c. It takes place in a very few minutes and is most rapid at the first instant of contact.

d. It is attended by a *rapid stiffening* of the mortar, *a rapid loss of workability* due to *rapid loss of water*. This stiffening is *not* hardening through cementing action and must not be confused with it.

e. The rapid stiffening of a mortar due to compacting on a porous base renders it impossible to make good contact between the mortar bed and the next course of bricks or to slush the mortar in cross joints when shoving bricks into place. It prevents the mortar in the horizontal bed on a course of bricks from slumping into and filling any vertical joints left open by the mason.

f. The unidirectional compacting pulls the mortar away from the bricks in the cross joints. The mortar is too stiff to flow under the pressure of bricks laid above it to cause any renewal of contact.

Lime and rich in lime mortars have high water retaining capacity and therefore tend to undergo a minimum of compacting when in contact with porous building units (see "Rate of Stiffening of Mortars on a Porous Base," Rock Products, September 10, 1932 issue).

(B) *Shrinkage During Early Hardening*

a. This type of volume change is omnidirectional.

b. It *attends* hardening through cementing action.

c. It occurs but once during the life history of a mortar.

d. Its magnitude is diminished when the mortar is in contact with an absorbent unit and is greatest when in contact with solids of zero porosity.

e. A mortar which hardens slowly is more or less plastic when most of this type of shrinkage is completed.

f. Any possible damaging effect of this type of volume change is dependent as much (and probably more) on the *rate of hardening* as on the magnitude of shrinkage.

g. Data obtained during an extensive study at the Bureau of Standards show conclusively that this type of volume change is not damaging either to the mortar or to the bond between the mortar and bricks. This was found to be true regardless of the magnitude of the shrinkage of mortar during early hardening. *Typical data* are given in Table 5. Had the shrinkage during hardening been damaging, then with mortars relatively high in such shrinkage, we would expect that the strength of bond when

TABLE 5

Negative Results Obtained in the Study of Any Possible Damaging Effect of Shrinkage During Early Hardening

Mortar Composition Lime: Cement: Sand (By Volume)	Shrinkage During Early Hardening (Initial 48 Hours) Per Cent	Strength of Bond in Tension at 3 months Averages of 3 Tests			
		Brick No. 3		Brick No. 5	
		With Lugs lbs./in.^{2}	Without Lugs lbs./in.^{2}	With Lugs lbs./in.^{2}	Without Lugs lbs./in.^{2}
0:1:3	0.21	45.8	53.4	26.4	28.0
0.15:1:3	0.30	51.5	61.5	51.3	48.2
1:1:6	0.34	40.4	41.0	35.0	27.4
2:1:9	0.44	33.4	36.2	22.0	22.5
3:1:12	0.63	17.6	19.6	17.0	13.5
1:0:3	0.66	14.8	15.5	11.9	12.9

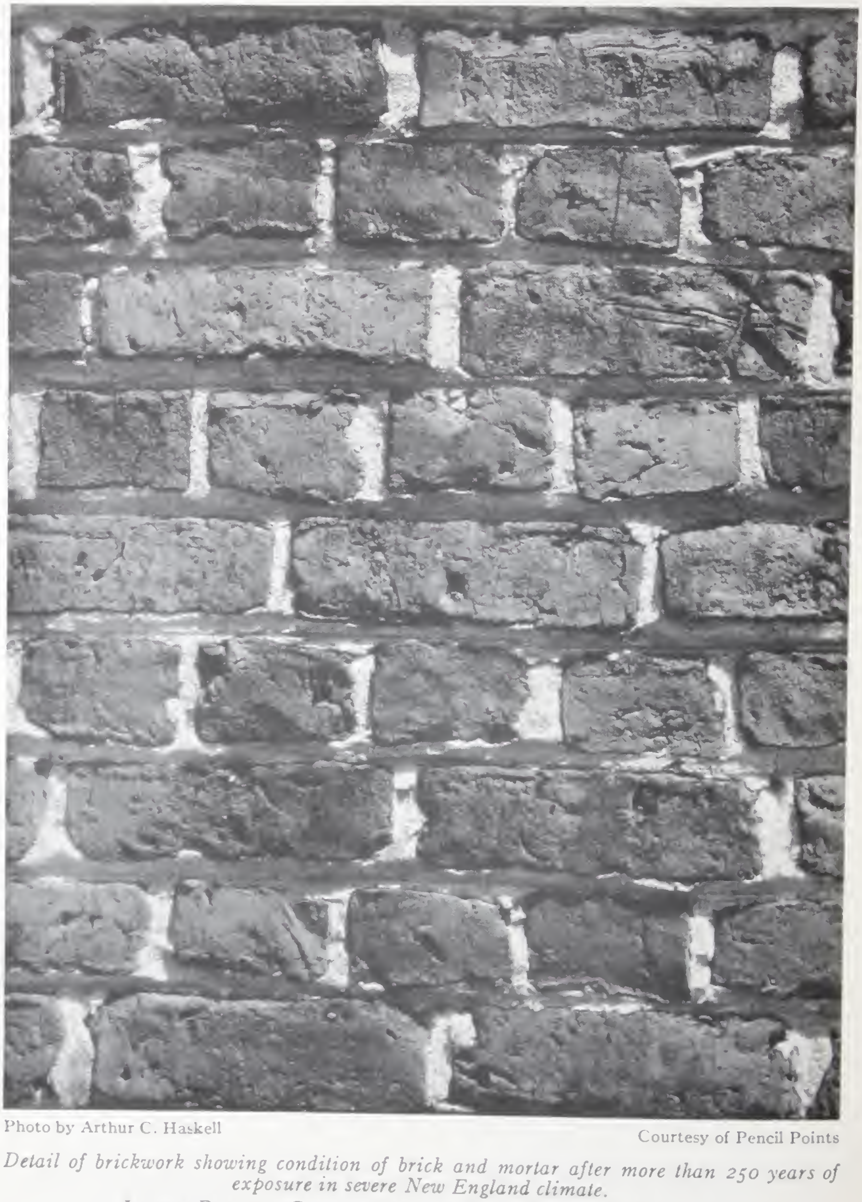

Photo by Arthur C. Haskell

Courtesy of Pencil Points

Detail of brickwork showing condition of brick and mortar after more than 250 years of exposure in severe New England climate.

JOSEPH PEASLEE GARRISON HOUSE, ROCK VILLAGE, MASSACHUSETTS
BUILT 1675—PHOTOGRAPHED 1933
Lime mortar used.

metal lugs were embedded in the joints would be very much less than that obtained without the lugs and that this difference would increase with the magnitude of such shrinkage. This did not happen. The data were obtained by bonding together the flat surfaces of two bricks with half-inch mortar joints. Three ⅜-inch lugs were embedded in the joints of half of the total number of the two brick-mortar specimens.

In table 5, most of the values obtained with lugs are slightly lower than those obtained without lugs but this difference was *apparently independent of the magnitude of the shrinkage during early hardening.* The slightly lower values obtained with lugs are explained on the basis of the fact that where the metal lugs touched bricks, mortar did not. There was slightly less bonded area with the lugs present.

Bricks 3 and 5 (Table 5) were about as impervious as any that could be found, a condition designed to augment the shrinkage during early hardening. The bricks were restrained from coming together as the mortar shrunk, a condition similar to that obtaining in the vertical joints of a wall. An intensive study of available information does not reveal any authentic data obtained by carefully controlled tests, that is in conflict with the conclusion that shrinkage during early hardening does not create openings between mortar and bricks.

(C) *Volume Changes Subsequent to Hardening*

a. This type of volume change is characterized by expansion on wetting and shrinkage on drying.

b. It is cyclic and frequently is rapid if the conditions for wetting and drying are favorable.

c. It takes place in rigid mortar that has an elastic limit.

d. High volume changes subsequent to hardening are characteristic of dense mortars of outstanding hydraulic properties. They are lowest for straight lime mortars. This type of volume change is reduced as lime is substituted more and more for portland cement (Bureau of Standards Research Paper No. 321, "Volume Changes in Brick Masonry Materials").

The data shown in Table 13 of Bureau of Standards Research Paper No. 683, "Properties of Mortars and Bricks and Their Effect on Bond," show that when the extent of bond is poor (less than 90 per cent of the flatside area of a brick) there is a tendency for it to be destroyed entirely if the mortar is one that has high volume changes subsequent to hardening.

If the extent of bond is complete or nearly so, high volume changes in the hardened mortar tend to produce cracks in a direction more or less perpendicular to the plane of contact of brick and mortar. These

cracks may heal slowly when the mortar is wet, but they occur again and again and tend to admit an excessive amount of water into the wall and, as a consequence, further occurrence of volume changes is accelerated.

Usually, a mortar having low water retaining capacity is one that also undergoes relatively high volume changes subsequent to hardening. This is an undesirable combination, for it usually results in a poor extent of bond coupled with conditions which tend to completely destroy the bond and leave "mortar pancakes" in the wall.

4. *EXTENSIBILITY*

Extensibility is here defined as the maximum linear deformation

TABLE 6

Extensibilities and "Factors of Safety" of Mortars, Age 3 months—Average of 3 tests

Mortar Composition Lime: Cement: Sand By Volume	Extensibility, inches per 100 inches	Maximum shrinkage subsequent to hardening inches per 100 inches	Factor of safety, values of second column divided by the corresponding values of the third column
0:1:3 (portland cement No. 1) (a)	0.026	0.084	0.31
0:1:3 (portland cement No. 2) (b)	0.025	0.071	0.35
0:15:1:3 (portland cement No. 1 and lime No. 3)	0.031	0.076	0.41
1:1:6 (portland cement No. 1 and lime No. 1)	0.028	0.038	0.74
2:1:9 (portland cement No. 1 and lime No. 1)	0.030	0.026	1.16
3:1:12 (portland cement No. 1 and lime No. 1)	0.025	0.010	2.50
1:0:3 (lime No. 1) (c)	0.031	0.007	4.43
1:0:3 (lime No. 2) (d)	0.028	0.004	7.00
1:0:3 (lime No. 3) (e)	0.022	0.001	22.00
1:0:3 (lime No. 4) (f)	0.025	0.006	4.20
1:1:6 (portland cement No. 2 and lime No. 1)	0.023	0.049	0.47
2:1:9 (portland cement No. 2 and lime No. 1)	0.024	0.027	0.90
3:1:12 (portland cement No. 2 and lime No. 1)	0.024	0.017	1.41
1:1:6 (portland cement No. 1 and lime No. 3)	0.022	0.037	0.60
2:1:9 (portland cement No. 1 and lime No. 3)	0.025	0.019	1.31
3:1:12 (portland cement No. 1 and lime No. 3)	0.024	0.013	1.85

(a) Portland Cement No. 1—Typical Grey Portland Cement meeting A.S.T.M. Standard Specifications.
(b) Portland Cement No. 2—White Portland Cement meeting A.S.T.M. Standard Specifications.
(c) Lime No. 1—Quicklime meeting A.S.T.M. Standard Specifications.
(d) Lime No. 2—Hydrated Lime meeting A.S.T.M. Standard Specifications.
(e) Lime No. 3—Hydrated Lime meeting A.S.T.M. Standard Specifications.
(f) Lime No. 4—Quicklime meeting A.S.T.M. Standard Specifications.

(stretching) that a hardened mortar may undergo before it fails in tension. It is a dimensionless value and may be expressed as inches per inch, inches per one hundred inches, etc. It happens that this property does not vary a great deal among mortars of different compositions, provided that the proportions of cementing materials to sand is 1 to 3 respectively, by volume, in all cases. In tests made during the cooperative investigation at the Bureau of Standards, the extensibilities of 50 different mortar compositions ranged from 0.014 to 0.035 per cent. The bulk of the specimens tested had extensibilities within the limits, 0.020 to 0.030 inches per 100 inches. These values were obtained by transverse tests and the extensibility was computed by dividing the modulus of rupture by the modulus of elasticity, it being assumed that failure was in tension, the mortar specimen acting as a beam supported at both ends and loaded in the middle.

The real significance of the property, extensibility, is its relation to the magnitude of volume changes subsequent to hardening. If the hardened mortar shrinks 0.10 of an inch per 100 inches and has an extensibility of 0.02 of an inch per 100 inches, its "factor of safety" would be $0.02 \div 0.10$ or $\frac{1}{5}$.

If the shrinkage of the hardened mortar is 0.01 of an inch and the extensibility is 0.02 of an inch per 100 inches of mortar, the factor of safety is $.02 \div .01$, or 2. The latter condition is surely more desirable than the former.

A factor of safety of 1 or greater (Table 6) is a desirable condition. With mortars of values appreciably less than unity there is likely to be either cracking open of joints (if the extent of bond is good) or shearing loose from the bricks or other units (if the extent of bond is poor). This danger is obviated by the use of lime or lime-portland cement mixtures that contain enough lime to keep the ratio of extensibility to maximum shrinkage of the hardened mortar above unity. Such mortars remain bonded to building units for years and few if any shrinkage cracks appear.

Table 6 contains data typical of those reported by the Bureau of Standards in the cooperative mortars and masonry investigation. (National Bureau of Standards Research Paper No. 683.)

5. *STRENGTH*

A strong wall is one having integrity, *i.e.*, adhesion of mortar to units throughout. "Mortar pancakes" that keep bricks apart and not together do not provide a strong wall, be the strength of the mortar what it may. A chain is only as strong as its weakest link. As we have seen this weakest link is at the plane of contact of bricks and mortar when the latter has poor bonding power. All other things being the same, a water-tight wall is always stronger than a leaky one. Under normal conditions a water-

tight wall will satisfactorily meet all ordinary requirements in the matter of strength in so far as masonry of the average load bearing type is concerned.

The following comments relative to strength of mortar are to be found in circular No. 30 of the National Bureau of Standards:

> "This question of the strength of a mortar is apt to be given undue weight. Since masonry is assumed to weigh 150 pounds per cubic foot, then the compressive load (in pounds per square inch) at the bottom of a wall will be $\frac{150}{144}$ times its height in feet. A mortar with a compressive strength of 100 pounds per square inch, should, according to this reasoning, be able to carry a wall $100 \times \frac{144}{150} = 96$ feet high, or about nine stories. The compressive strength of the mortar is usually measured by crushing 2-inch cubes. For a homogeneous material the unit compressive strength varies with the shape of the specimen, being dependent upon the ratio between the least horizontal dimension and the height. In a cube, this ratio is one. A mortar joint in a wall may possibly be 9 inches wide by 30 feet long by ½ inch thick. In this joint the ratio is $9 \div \frac{1}{2} = 18$. If a mortar has a strength of 100 pounds per square inch when tested in the form of a cube, it should theoretically have a strength of 1800 pounds per square inch when laid up in the wall."

Much consideration has been given to the compressive strength of brick

TABLE 7

(Data typical of those in Table 13, National Bureau of Standards Research Paper No. 683)

Transverse Tests of Brick Beams (5 bricks, single tier, 4 intervening mortar joints) Values are Averages of Three Tests. Beams Aged Three Months.

Average Modulus of Rupture

Mortar Composition Lime: Cement: Sand (By Volume)	Brick No. 1 Set Wet	Brick No. 2 Set Wet	Brick No. 3 Set Dry	Brick No. 4 Set Wet	Brick No. 5 Set Dry	Brick No. 6 Set Wet
	lbs./in.²	lbs./in.²	lbs./in.²	lbs./in.²	lbs./in.²	lbs./in.²
0:1:3	52.0*	208.0	39.4*	100.7	18.2*	0.0*
0.15:1:3	19.7*	132.3*	38.8*	126.0	4.1*	149.2*
1:1:6 (Lime No. 1)	56.6	66.8	73.5	90.5	15.8	104.7
1:1:6 (Lime No. 2)	42.9	47.6	68.2	88.8	6.8	122.9
2:1:9 (Lime No. 2)	45.1	42.0	39.9	83.4	10.4	88.7
3:1:12 (Lime No. 1)	29.8	24.2	30.4	35.0	15.2	42.1
1:0:3 (Lime No. 2)	28.5	32.2	39.3	26.8	13.0	32.9

*Poor extent of bond obtained with at least one of the 3 specimens.

WOMAN'S WARD, WESTERN STATE HOSPITAL, FORT STEILACOON, WASH.
ARCHITECTS: HEATH, GOVE & BELL, MOCK & MORRISON.
Mortar proportions were two volumes lime putty, one volume portland cement and nine volumes sand.

piers. It is interesting as well as enlightening to consider the results of flexural tests. On page 67 of "Impervious Brick Masonry," publication by the Alton Brick Co., St. Louis, Mo., the results of some flexural tests with two brick-mortar specimens are given. The average modulus of rupture was 41.9 lbs. per square inch with portland cement mortar and 79.7 lbs. per square inch with a 1 lime: 1 portland cement: 6 sand mortar, using the same brick (6 per cent total absorption) in both cases.

A poor bond is not as noticeable in compression as it is in flexural tests. There have been far less data obtained by the latter than by the former tests. Unfortunately all too many investigators have overlooked the fact that a brick pier of relatively enormous compressive strength may also be one in which the extent of bond is poor throughout. The same pier when subjected to a test for permeability will often leak like a sieve.

The data of Table 7 are taken from those of Table 13 of National Bureau of Standards Research Paper No. 683, "The Properties of Bricks and Mortars and Their Relation to Bond."

The reader may note that widely divergent values were obtained with the portland cement and the portland cement plus 0.15 volumes of lime mortars. The average modulus of rupture of the beams with the portland cement mortar and Brick No. 3 (of very low absorption) was the same as that obtained with the lime mortar and this brick. This was due to *poor extent of bond* in the former case.

Brick No. 5 (practically zero absorption and of a glassy surface) gave low bond strength with all mortars. However, with the more workable mortars, the extent of bond was good with this brick.

Some of the individual values obtained with the first two mortars (Table 7) were zero, owing to the fact that when the time came for testing the beams it was found that these mortars, poorly bonded initially (due to segregation in the mortar), had come loose from the bricks during the aging period. The same beams were intact during the first 4 weeks, hence it is concluded that the bond in these cases was disrupted through the relatively high volume changes subsequent to hardening, characteristic of these two mortars. The poor extent of bond in Figure 2 is an illustration of the functioning of the first mortar of Table 7 in the beam tests.

Many authorities recommend that porous bricks be wetted to improve the extent of bond. In obtaining data of Table 7, the porous bricks, Nos. 1, 2, 4 and 6 (ranging from medium to high absorption) were all wetted by total immersion for 15 minutes just before laying them. The mortars of low water retaining capacity tended to *segregate* even though they could not lose water through brick suction. High water retaining capacity is *always essential* with *all types of units*. Moreover, mortars deficient in this property are *usually* characterized by relatively high volume changes subsequent to hardening. These two undesirable properties, low water retaining capacity and high volume changes subsequent to hardening, are *usually associated*. The same holds for the *desirable combination*, high water retaining capacity and low volume changes subsequent to hardening, and *this desirable combination does more to promote strength in a wall of masonry than mortar strength per se*. This fact should be appreciated and thoroughly borne in mind by all who are interested in improving unit masonry from the standpoint of both strength and water-tightness.

The greater the divergence of the average values of Table 7, with any individual mortar with the 6 makes of brick, the poorer was the adaptability of that mortar and conversely. For example, values range from zero to 208 lbs. per square inch with the straight portland cement mortar and from 15.2 to 42.1 lbs. per square inch with the 3 lime: 1 portland

cement: 12 sand mix. This checks the data of Table 3 and with a different type of test specimen.

Bricks have received more than their just share of blame for the trouble, lack of bond. The fact that today there are more extreme types of building units on the market than obtained in times past, renders it all the more necessary that only adaptable mortars be used. As we have seen from actual data, an adaptable mortar is an important factor in obtaining strength of masonry.

School Board Administration Tower and Central School Building
Tacoma, Wash.

ARCHITECTS: HEATH, GOVE & BELL CONTRACTORS: F. H. GOSS CONSTRUCTION COMPANY

Mortar proportions were two volumes lime putty, one volume cement, and nine volumes sand. Mortar in excellent condition after more than 20 years of weathering.

6. *WEATHER RESISTANCE*

Two factors control the resistance to frost in unit masonry. These are:

1. The extent to which the wall becomes saturated during its life history and,
2. The frost resistance of the building materials (units and mortar).

The first of these two factors is much more important than the second. A comparatively dry wall is not exposed to weathering from severe climatic action. Water is the universal solvent and chief weathering agent. When water which saturates a wall is repeatedly frozen and thawed the masonry is disrupted regardless of the fact that the materials composing it may, in themselves, be frost resistant in the usual laboratory tests. The extent of bond between units and mortar in such a wall is poor to begin with, else the masonry would not be excessively saturated. A poorly distributed bond (not complete in extent) soon fails entirely from frost action.

The freezing and thawing of moisture which, under the most severe conditions, only dampens or partially saturates the wall, does relatively little damage. In such a wall, the extent of adhesion between mortar and units is good. The bond is therefore relatively durable both because it is uniform and complete and because it is subjected to a minimum of exposure.

It so happens that those mortars which have the best freezing and thawing records in laboratory tests are usually associated with leaky masonry. The properties that enable them to endure severe freezing and thawing in the laboratory are not properties which cause them to bond completely and firmly to various types of building units. It also happens that those mortars of relatively less resistance to laboratory freezing and thawing are usually associated with dry walls. They have properties which insure good adhesion at all points throughout the wall. It is more important to avoid excessive exposure of a wall than it is to have materials that are the most resistant when severely exposed. Immunity from the condition, excessive wall saturation, is more essential than the ability of the materials composing the wall to endure excessive saturation. Excessive dampness in itself is damaging both to health and property.

Lime mortar has an enviable record for resistance to weathering in the oldest brick buildings in the history of this country. The walls in these fine old buildings seldom if ever became completely saturated. Therefore the lime mortar did not decay and fall out.

Due regard and care should be given to the subjects, design, construction, workmanship and maintenance. Masonry should not be too freely

Photo by Arthur C. Haskell — Courtesy of Pencil Points

HOLLIS HALL—HARVARD UNIVERSITY, CAMBRIDGE, MASSACHUSETTS
BUILT 1763—PHOTOGRAPHED 1933
Lime mortar with a record of 170 years of service in a severe climate.

exposed, walls should be furred, parapet walls should be protected and sills, copings, etc., should be properly flashed. *However, attention to these details alone will not prevent excessive saturation of a wall.* With these precuations there must be a judicious selection of mortar materials on the basis of the results of exhaustive research in the field of mortar properties.

Lime and rich in lime mortars attain their full strength at a rate less rapid than that of portland cement mortars. Many of the natural cements and hydraulic limes also attain their full strength at rates comparable to that of lime mortars. To subject specimens of mortars having a relatively slow rate of attaining strength to severe laboratory freezing and thawing tests at an early age is a procedure that can only add to an accumulation of "*mis*information" which is of no practical value. The number of cycles of freezing and thawing provided for in the usual laboratory procedure before specimens have aged a year is more than would be attained, even in a leaky wall, in half a century of normal exposure. The proof of this statement is found in the many examples of old masonry in both the United States and Europe made of materials which of themselves give negative results under prescribed laboratory tests, yet these buildings stand today in mute testimony of their endurance after centuries of exposure.

7. *EFFLORESCENCE*

All building materials contain at least some trace of water soluble substances that can appear on the exterior wall surface *if there is excessive saturation of the wall.*

Table 1 of National Bureau of Standards Technologic Paper No. 370, "Cause and Prevention of Kiln and Dry-House Scum and of Efflorescence on Face-Brick Walls," shows the superiority of lime mortar from the standpoint of water soluble salt content.

Use lime and keep the wall dry.

J. A. Van der Kloes, in an article, entitled "Influence of the Qaulity of Mortar on Masonry," Quarry, 1911, 16, pages 204-7, states that he does not "remember ever having seen efflorescence on brickwork set in lime mortar of *only lime,* fat or hydraulic, and sand."

M. Hasak, in "Was der Baumeister vom Mörtel Wissen muss," pages 67-69, Berlin, 1925, Kakverlag, G. m.b.H., deprecates the use of cement mortar on account of its liability to cause efflorescence.

In the British Building Research Station Special Report No. 18, "The

Weathering of Natural Building Stones," by R. J. Schaffer, there is found on page 63: "In the experience of the Building Research Station, cement mortars are found to be somewhat more liable to cause efflorescence than lime mortars, although hydraulic lime mortars are not always entirely immune."

These statements are not opinions. They are founded on facts. Moreover, the use of rich in lime mortars promotes dry walls and in so doing tends to avoid efflorescence.

8. *RATE OF HARDENING*

Some have expressed skepticism about the use of lime or rich in lime mortars for the reason that they believe that such mortars harden too slowly to meet the needs of modern construction. Let the facts dispel such an illusion.

TABLE 8

Rates of Hardening of Mortars on an Impervious Base as Indicated by Vicat Tests

Mortar Composition Lime: Portland Cement: Sand (Proportions by Volume)	Rates of hardening. Averages of 3 tests. Values obtained with a modified vicat apparatus after the mortar had been on an impervious (steel) base for 2 hours. Millimeters penetration in 30 seconds.
0:1:3 (portland cement No. 1)	5.2
0:1:3 (portland cement No. 2)	0.8
1:1:6 (portland cement No. 1, lime No. 1)	1.8
2:1:9 (portland cement No. 1, lime No. 1)	3.8
3:1:12 (portland cement No. 1, lime No. 1)	4.0
1:1:6 (portland cement No. 2, lime No. 2)	1.0
2:1:9 (portland cement No. 2, lime No. 2)	2.5
3:1:12 (portland cement No. 2, lime No. 2)	3.5
0.15:1:3 (portland cement No. 2, lime No. 2)	0.4
1:1:6 (portland cement No. 1, lime No. 4)	2.5
2:1:9 (portland cement No. 1, lime No. 4)	1.9
3:1:12 (portland cement No. 1, lime No. 4)	2.5
0.15:1:3 (portland cement No. 1, lime No. 4)	1.8
1:0:3 (lime No. 1)	30.0
1:0:3 (lime No. 2)	22.7

Portland Cement No. 1—Typical Gray Portland Cement meeting A.S.T.M. Standard Specifications.
Portland Cement No. 2—White Portland Cement meeting A.S.T.M. Standard Specifications.
Lime No. 1—Quicklime meeting A.S.T.M. Standard Specifications.
Lime No. 2—Hydrated Lime meeting A.S.T.M. Standard Specifications.
Lime No. 4—Quicklime meeting A.S.T.M. Standard Specifications.

TABLE 9

Mortar Mixes for Various Types of Masonry

Masonry Type	Type of Construction	Loading	Mortar Proportions (Volume) Lime : Cement : Sand	Remarks
Common and face clay, shale or sand-lime brick.	Dwellings, garages and similar construction.	Any condition of loading for such types of construction.	1:0:3 1:0:3 1:0:3	
Clay or shale brick.	Walls and piers below grade continuously exposed to wet or damp conditions.	Ordinary distributed Heavy concentrated Earthquake tremors.	1:1:6* 1:1:6* 1:1:6*	
Common and face clay, shale or sand-lime brick.	Exterior walls and piers above grade.	Ordinary distributed Heavy concentrated Earthquake tremors	2:1:9* 2:1:9* 2:1:9*	2:1:5 Mortar for domestic and power plant chimneys.
Granite, limestone, marble, sandstone, terra cotta facing and trim.	Exterior walls and piers above grade.	Ordinary distributed Heavy concentrated Earthquake tremors	2:1:9* 2:1:9* 2:1:9*	Use non-staining portland cement and washed sand.
Common and face clay, shale or sand-lime brick, concrete brick.	Interior walls and piers above and below grade.	Ordinary distributed Heavy concentrated Earthquake tremors.	2:1:9* 2:1:9* 2:1:9*	
Hollow clay tile, concrete block, concrete tile, cinder block, gypsum block.	Exterior walls above grade and interior partition walls.	Non-bearing partitions, exterior and bearing walls and partitions.	2:1:9* 2:1:9* 2:1:9*	

Notes: Materials to conform to current "A.S.T.M. Standard Specifications."
Mortar containing portland cement to be used within one hour after mixing.

* One volume of cement is the maximum quantity which should be used The sand content is to be varied in accordance with its quality in the particular market involved and its proportion may be reduced if greater mortar strength is desired.

Lime mortar containing no cement does harden slowly on an impervious building unit. With more porous units such as dry-press bricks there should be no difficulty whatsoever. Lime mortar is particularly suitable with very porous units set dry in winter construction. The bulk of the water is out of the mortar and in the brick before it can be frozen. At the same time the lime mortar is sufficiently retentive of water to make the necessary intimate contact with the highly porous units without necessitating wetting such units to any extent whatsoever. Bricks should never be wetted when laid in freezing weather.

Table 8 gives typical data obtained during a cooperative investigation as recorded in National Bureau of Standards Research Paper No. 683.

Complete data covering 50 mortar compositions studied may be obtained from the National Lime Association, Washington, D.C., on request. The higher the value of the second column, Table 8, the more slowly did the mortar harden on the impervious base.

MORTAR RECOMMENDATIONS

From the foregoing study of essential mortar properties it is apparent that lime mortar meets all of the requirements, including strength of masonry, for most purposes.

However, in order to avoid delay, where rapid methods of modern construction are employed, the addition of portland cement to lime mortar is recommended, even though this practice adds to the cost of construction and often results in considerable sacrifice in quality of the finished masonry. When cement is so added it replaces an equivalent volume of lime in the mortar mixture.

It must be remembered that *as portland cement is substituted more and more for lime, there is a greater and greater sacrifice of the essential properties, water retaining capacity, workability, adaptability, bonding power, and low volume changes subsequent to hardening.*

Laboratory and service tests have both shown that a mortar consisting of two volumes of lime, one volume of portland cement and nine volumes of sand is well adapted for use with a wide variety of units and under a wide variety of conditions, it is therefore recommended for general use where a mortar having a rapid rate of hardening is required. If it is desired that the mortar strength be increased, it is recommended that the sand content be reduced to 7 or 8 volumes but that the ratio, 2 volumes of lime to 1 volume of portland cement, be maintained. This procedure will increase mortar strength with no sacrifice of the more essential properties.

For walls and piers below grade and for masonry that is continuously exposed to wet or damp conditions, a mortar consisting of one volume each of lime and portland cement together with six volumes of sand is recommended.

Table 9 is a list of recommended mortar mixes for various types of masonry, in different locations and under different loading conditions. These data should be useful as a reference in the drafting or revision of municipal, state and sectional building codes, and in the preparation of specifications for engineering and building construction.

Famous Old Shot Tower, Baltimore, Md. constructed in 1847

Common brick bonded with straight lime mortar. A fine example of the enduring quality of masonry laid up in lime mortar.